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COST/PERFORMANCE ANALYSIS OF AN INDUCTION LINAC DRIVER SYSTEM FOR INERTIAL FUSION*

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Abstract

A linear induction accelerator that produces a beam of energetic (≈ 10 GeV) heavy (A ≈ 200) ions is a prime candidate as a driver for inertial fusion. Continuing developments in amorphous iron for use in accelerating modules represent a potentially large reduction in the driver cost and an increase in the driver efficiency. Additional insulator developments may also represent a potentially large reduction in the driver cost.

The efficiency and cost of the induction linac system is discussed as a function of output energy and pulse repetition frequency for several beam charge states, numbers of beams and beam particle species. Accelerating modules and transport modules will be described. Large cost leverage items will be identified as a guide to future research activities and technology of development that can yield further substantial reductions in the accelerator system cost and improvement in the accelerator system efficiency.

Introduction

The use of heavy ion accelerators as drivers to initiate inertially confined fusion reactions has been under study since 1976.[1] Early heavy ion accelerator concepts to provide 1 to 10 MJ of 5 to 20 GeV ions of atomic mass between 130 and 210 amu included an rf linac-accumulator system, a synchrotron-accumulator system, and an induction linac system.[2] Recent designs have concentrated on the rf linac-accumulator system as an ICF driver for the HIBALL study,[3] and, at Lawrence Berkeley Laboratory, on an induction linac which does not require an accumulator because the beam pulse duration is compressed during acceleration. This paper describes the tools and current results of a cost-performance study of an induction linac to drive an inertial fusion power plant.

Cost Optimization Code LIACEP

The LBL Linear Induction Accelerator Cost Evaluation Program (LIACEP) is an optimization program that varies several of the physical parameters of an induction linac in search for a minimum cost combination.[4] In addition to estimating the accelerator system cost and efficiency, LIACEP can be used to identify the components and materials that have a high leverage on the cost and efficiency of the accelerator system. These high leverage items are logical areas for research and technology development to reduce the cost and increase the efficiency of the accelerator system.

In using LIACEP, the ion mass and charge, the normalized transverse emittance, single particle and depressed betatron phase advance per period of the transport lattice, number of beamlets, charge per beamlet, and pulse repetition frequency are set. Also set are engineering parameters such as clearances, the acceleration module core material, and various limits to insulator voltages, module size, etc. Then, for a given particle kinetic energy, current and focussing system packing fraction, the required field at the beamlet edge, the maximum beamlet envelope radius, and the half period of the transport lattice are determined using the approximation of Lee et al.[5] These are used as input into a focussing system subroutine, which consists of a description of either pulsed quadrupoles or superconducting quadrupoles. From the focussing system subroutine, the quadrupole length and the accelerator inner radius are obtained, as well as focussing system costs and power consumption that satisfy constraints on the maximum pole tip field and beam radius and the minimum half period length to beam radius ratio. The acceleration system subroutines are then used to determine the accelerator module dimensions, power requirements, and costs for each module design. A cost comparison subroutine selects the minimum cost alternative of the various acceleration module designs. The current is increased through a range limited by focal constraints and the calculation repeated, from which the minimum cost current is selected. Next, the packing fraction is increased and the calculations repeated. After the optimization at one particle kinetic energy point is completed, the process is repeated at a higher kinetic energy level. Finally, the total cost, length, power, efficiency, etc., are determined for this minimum cost accelerator system.

The module options investigated in the LIACEP are of three types.[6] The first type consists of cores external of the beam but internal to the insulator. The second type has the insulator external of the beam and internal to the cores. The third type is similar to the second type, but has an accelerator core wrapped around the focussing element. In most runs, the cost-optimized design option uses the type 3 modules in the low voltage portion of the accelerator (< 1000 MV) and the type 2 modules in the high voltage region. The core material options in LIACEP include amorphous iron, nickel iron, iron, and silicon iron, which are compared to ferrite cores.

Cost Studies

Three cost studies are underway. The purpose of the first study was to examine the state of LIACEP, and to vary some of the physical parameters of an induction linac to examine their cost leverage. The purpose of the second study is to examine the effect of a large parameter space of ion species, kinetic energies, emittances, beam energies, pulse repetition frequencies, and the number of beamlets on the minimized cost and the resultant efficiencies of an induction linac to be used in power plant system studies

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for the Heavy Ion Fusion Systems Assessment Project. The third study is based on several possible power plant sizes, reactor chamber target yield capabilities, and target gain curves to identify the requirements of the linear induction accelerator driver, and using LIACEP, to determine its cost and efficiency.

In all these cases, the accelerator system assumes an initial voltage of 50 MV, and the costs do not include the low voltage (< 50 MV) portion of the accelerator, nor do they include the final compression, transport, and focussing portion of the energetic ion beam to the target. These sections receive a separate treatment in the systems study due to their distinctive roles and technologies. However, their costs are expected to be small compared to the accelerator.

Effects of Physical Parameters on Cost

A preliminary problem was run to determine the current state of LIACEP. This exercise reproduced the results presented by Faltens et al.[7] for a 200 amu, unity charge state ion (Hg^+) using 4 beamlets of 75μ coulombs per beamlet and a total output energy of 3 MJ. The accelerator input voltage is 50 MV and the output voltage is 10 GV. The normalized transverse emittance is 1.17×10^{-5} meter-radians per beamlet and the tune is depressed from 60° to 24°. The acceleration cores are of amorphous-iron, and the focussing is by superconducting quadrupoles. The pulse repetition frequency is 1 hertz, which is lower than will be used for a fusion power plant and results in a relatively low efficiency because the transport system and acceleration system power requirements are comparable at 1 Hz. Increasing the pulse repetition frequency increases substantially the accelerator system efficiency.

The Reference Case above is used as a base for comparison with other runs with changes in some of the material properties assumed in the accelerator design. One such property is the vacuum insulator flashover as a function of pulse duration, which has an appreciable effect on the system cost and efficiency. The assumed design limits for flashover gradient vary from more than 20 kV/cm for sub-microsecond pulses to 5 kV/cm for pulse lengths of 1 μs and longer. There are few, if any, 1 meter diameter, several meter long graded accelerating columns with several megavolts applied across them, let alone data on their time dependent flashover. Yet, it is permissible to examine the consequences of varying these limits. Increasing the short time flashover field by a factor of 2.5 will decrease the system cost by 13% and increase efficiency by 75%. Doubling the long pulse flashover field will reduce the cost by 14% and increase efficiency by 13%. Doing both will reduce cost by 24% and increase efficiency by 11%. Clearly, this provides motivation for investigation of the usable fields in a realistic structure and environment.

Increasing the breakdown voltage across vacuum gaps does not affect the cost of the accelerator system. This is due to the high cost of the insulator which requires the insulator to be located between the acceleration core and the beam such that the regions between the acceleration cells in the module can be insulated. However, if the cost of the insulators can be reduced such that the core costs prevail and the insulators must be placed outboard of the cores for a minimum cost acceleration module, the breakdown voltage across vacuum gaps will become important to the cost of the system.

The effect of the voltage breakdown of ceramic insulators in vacuum as a function of length on the cost and efficiency of the accelerator system was also investigated. The current allowable design curves allow about 38% of the voltage holdoff properties of high-power microwave tubes presented by Staprans,[8] and is about 80% of the voltage breakdown gradient of porcelain. By using a design curve at 40% of Staprans holdoff properties, which is the breakdown gradient for porcelain, the cost of the accelerator can be decreased about 11%, and the efficiency increased about 14%. Re-X, a General Electric castable insulator, has about 80% of the voltage breakdown gradient of porcelain, such that it lies on the current design curve. However Faltens recommends operating at about half the voltage breakdown gradient,[9] which will change the cost of the accelerator system. However, the performance of the insulators can be increased by more frequent subdivisions using gradient rings. But, because the cost of the Re-X insulators is expected to be substantially less than that of porcelain insulators, there may be a cost advantage to using the somewhat lower performing Re-X insulators in the accelerator system. The cost of Re-X will be entered into the LIACEP data base and the effect of the cost and performance of Re-X on the cost and efficiency of the accelerator system will be investigated.

To date we have identified the surface vacuum flashover gradient as a function of pulse duration for short pulses as a potential high-leverage field of research for induction linacs to be used as inertial fusion drivers. An experimental program that identifies the variables that affect short pulse flashover and determines the effects of 10^8 pulses on flashover will be cost-effective.

In addition, further studies on voltage breakdown as a function of length for ceramic insulators in vacuum may be cost effective. Of special interest is the effect of size and configuration on the breakdown.

Using the reference case, but with the pulse repetition frequency increased to 5 hertz, the cost was examined as a function of beam energy, where the beam energy was varied by varying the beam charge. The cost varied as a constant plus a linear term with energy. An increase in energy from 1 to 10 MJ results in an increase in cost by a factor of 3.3. For an output beam energy of 3 MJ, the cost varied as a constant plus a linear term with the pulse repetition frequency. For an increase in frequency from 1 to 10 hertz, the cost increased by only 8 percent. For the reference case at 5 hertz the number of beamlets was varied between 1 and 16, with the minimum cost of 8 beamlets only 3.5% less than the cost of 4 beamlets.

Heavy Ion Fusion Systems Assessment Project Accelerator Cost Study

The Heavy Ion Fusion Systems Assessment Project sponsored by the DOE and EPRI is investigating the economic aspects of potential heavy-ion driven ICF power plants over a large parameter space.[10] To facilitate this, LIACEP is being used to perform the cost and efficiency studies for an induction linac. The accelerator parameter space being investigated for this study is given in Table I. The selection of a tune of 60° and depressed tune of 24° is conservative, as somewhat larger undepressed tunes and much smaller depressed tunes have been demonstrated in the laboratory in small scale experiments. The amorphous iron cores were selected because they were calculated to cost only about 67% of the silicon iron cores, and less than half of the nickel iron cores, and will operate at an efficiency of greater than 1.5 times that of the other core material.

Qualitatively, the results of the parameter space investigated to date for the Heavy Ion Fusion Systems Assessment Project show that the increase in accelerator cost with beam energy increases more rapidly for low kinetic energy ions on target than for higher kinetic energy ions of the same mass. At a given beam energy and ion kinetic energy, the accelerator cost increases with the ion mass. The cost of the accelerator decreases with an increase in emittance over the parameter space investigated. Finally, the accelerator efficiency is related to the cost of the accelerator in that, in general, the highest efficiency accelerators tend to have the lowest optimized cost; moreover, efficiency can be increased by higher cost tradeoffs about the cost optimized designs, if necessary.

Table I.
Accelerator Parameter Space Investigated for Heavy Ion Fusion System Assessment

Ion Mass	130, 160, 190, 210 amu
Ion Kinetic Energy	5, 10, 15, 20 GeV
Beam Energy	1, 2, 3, 5, 10 MJ
Emittance (un-normalized)	1.5×10^{-5}, 3×10^{-5} m-radians
Pulse Repetition Frequency	5, 10, 15, 20 hertz
Number of Beamlets	4, (8), (16)*
Ion Charge State	+1
Tune : 60°, Depressed Tune : 24°**	
Initial Ion Kinetic Energy	50 MeV
Focussing System : Superconducting Quadrupoles	
Core Material: Amorphous Iron	

*( ) - not completed
**Recent experiments show that depressed tune of 8° can be achieved. This will lead to cost savings.

Accelerator Cost Study Based on Target Performance and Fusion Power

This portion of the accelerator study is based on the ICF reactor constraints and fusion power. Monsler et al. have identified the yield constraints on several generic reactor concepts.[11] The cost of a power plant is dependent on the fusion power output. This study is based on fusion powers of 1500, 3000, and 6000 MW_f and target yields of 300, 600, and 1200 MJ, which cover several generic types of reactor chambers. The pulse repetition frequencies of the accelerator system can be determined from the target yield and fusion power. The accelerator energy can be determined for a given target yield from the Lindl-Mark gain curves.[12] Using the upper bound of the best estimate gain curve, the $r^{3/2}R$ parameter can be determined where r is the spot radius (cm) and R is the range of the ions in the target material (grams/cm^2). From the constraints on the gain curve that $0.1W^{1/3} < r < 0.2W^{1/3}$, where W is the accelerator energy (MJ), the bounds on the spot size r can be determined. From the spot size r, the maximum emittance of the accelerator can be determined, assuming either no momentum spread or that chromatic aberrations are negligible in the final beam transport and focussing lenses. Then, the range can be determined based on the spot size. For a given ion mass, the ion kinetic energy can be determined from the ion range-kinetic energy curves of Bangerter et al..[13] In addition, the normalized transverse emittance and the total beam charge can be determined.

For an ion mass of 200 amu, the ion kinetic energy and normalized emittance as a function of target yield or accelerator output energy are shown in Figure 1 for the upper, middle, and lower bounds on the spot radius for which high confidence exists in the gain curves. For a given $r^{3/2}R$, the range for the lower bound spot radius must be greater than for the upper bound spot radius. This requires, for a given ion mass, higher kinetic energies of the ions for the lower spot radius. The effect of the higher ion kinetic energy for the smaller spot radius is to reduce the normalized transverse emittance below that of the larger spot radius.

The minimum normalized cost of the accelerator system per unit fusion power as a function of target yield or accelerator output energy for the upper and lower bounds on the spot radius and several fusion powers is shown in Figure 2. The tune depression of the accelerator system is from 75° to 24°, and the normalized cost is based on the cost minimum of 4, 8, and 16 beamlets. The normalized cost for the lower bound spot radius is minimized at 8 beamlets, while that for the upper bound spot size is minimized at 16 beamlets. The intermediate spot radius shown for the 1500 MW_f case is also minimized at 16 beamlets.

For a given accelerator energy, costs tend to vary inversely within the final ion energy due to the increased beam charge for a fixed normalized transverse emittance and tune depression. Thus, the normalized cost of the maximum spot radius should be more than that of the minimum spot radius because a lower ion kinetic energy is associated with the maximum spot radius. The increased normalized emittance associated with the maximum spot radius tends to reduce the cost differential between the maximum and the minimum spot radius. However, the cost of acceleration of the lower ion kinetic energy (associated with the maximum radius) is more sensitive to the number of beamlets than that of the more energetic ions (associated with the minimum radius) for a fixed accelerator energy.

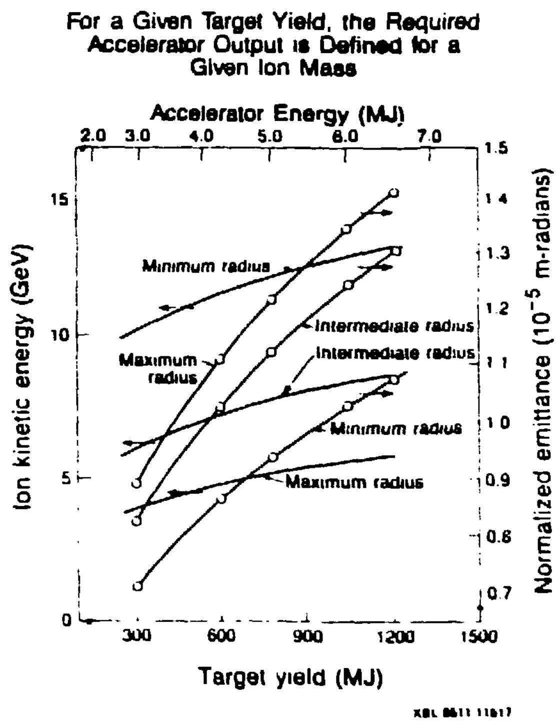

Fig. 1.
Accelerator Parameter Space as a Function of Target Yield for a Range of Target Spot Radii for Ion Mass 200 amu.

For a Given Target Yield and Fusion Power, the Accelerator Costs can be Estimated Using LIACEP

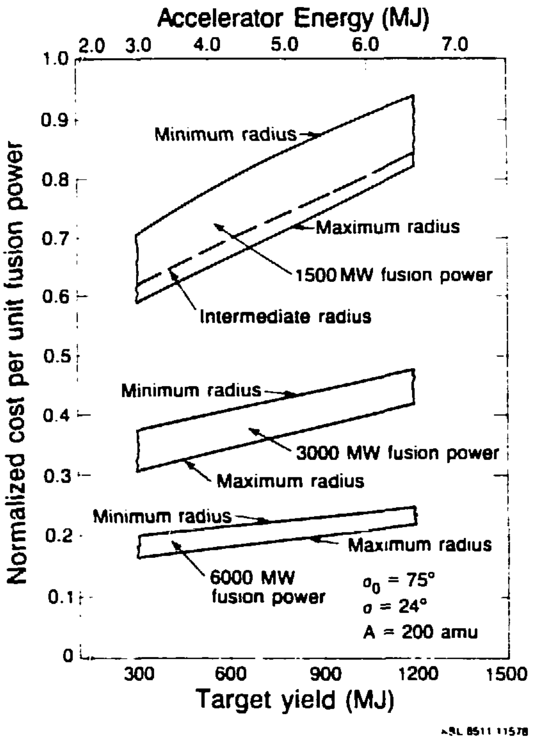

Fig. 2.
Normalized Cost of Accelerator Per Unit Fusion Power as a Function of Target Yield for Several Fusion Power Outputs and a Range of Target Spot Radii for Ion Mass 200 amu.

A final consideration for this section of the analysis is the accelerator efficiency and ratio of fusion power to accelerator input power. For the minimum normalized case shown in Figures 1 and 2, the lowest accelerator efficiency is about 22% ranging to a maximum of about 32%. The minimum ratio of fusion power to accelerator input power is about 22 ranging to about 52. This ratio is substantially greater than the minimum goal of 10 and the desired goal of 20 for inertial fusion.[11]

Conclusions

The LIACEP optimization program is a valuable tool for analyzing an induction linear accelerator. LIACEP coupled with range-energy and target gain curves can be used to explore the accelerator-target parameter space, and to identify promising accelerator-target combinations for further study. LIACEP can be used to identify high-leverage fields of research and technology development that will reduce the cost of a heavy ion induction linac as a driver for inertial fusion. One potential high-leverage field of research is the surface vacuum flashover gradient as a function of pulse duration for pulses less than 1 microsecond long. Other potential high-leverage fields of research and development include improved core and insulator materials at low costs.

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